Tillage and Nitrogen Fertilizer Influence on Carbon and Soluble Silica Relations in a Pacific Northwest Mollisol

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ABSTRACT

Long-term experiments are ideal for evaluating the influence of agricultural practices on soil organic carbon (SOC) accretion. Little is known about the influence of tillage and N fertilization on SOC distribution and silica (Si) movement in a soil. This study: (i) determined the effect of tillage and N fertilizer on SOC accretion in a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll), and (ii) examined the subsequent influence of fine organic matter (FOM) on Si movement. A long-term wheat (*Triticum aestivum* L.)–fallow experiment was established in 1940, in a randomized block with split-plot design. Soil cores (2-cm increments) from two tillages (moldboard plow, MP; and sweep, SW) and two N rates (45 and 180 kg N ha^{-1}) were used to measure coarse organic matter (COM), FOM, pH, bulk density (ρ_b), water-soluble C (C_{ws}), and water-soluble Si (Si_{ws}). The FOM fraction (6.6 kg C m^{-2}) in SW was 14% higher (5.8 kg C m^{-2}) than in MP for the 180 kg N ha^{-1} rate. After 44 yr of N additions, the SOC storage (6.2 kg C m^{-2}) for the 180 kg N ha^{-1} rate increased 3% above that for the 45 kg N ha^{-1} (6.0 kg C m^{-2}). Total Si_{ws} in the B horizon were 34 and 39% greater than in the Ap horizon for the MP and SW systems, respectively. Interaction of tillage and N with Si_{ws} suggests that SOC provides a mechanism to suppress Si solubility, which impacts siliceous pan formation, reduces soil mechanical resistance, and enhances drainage and plant growth.

S TORAGE OF C AND N in a Walla Walla silt loam has been remarkably sensitive to long-term tillage and N fertilization in a semiarid climate (Rasmussen and Rohde, 1988; Rasmussen and Collins, 1991). After 44 yr of the SW system, soil organic N (SON) and SOC in the top 7.5 cm of soil increased 26 and 32%, respectively, compared with the MP system (Rasmussen and Rohde, 1988). They also noted that 18% of the applied N was retained in soil organic matter, and that SW retained 5.7 kg ha^{-1} yr^{-1} more N than MP system. Bulk density and pH in the surface 30 cm were sensitive to long-term treatments (Pikul and Allmaras, 1986). Pikul and Zuzel (1994) reported a 12% increase in surface crust porosity with fertilizer addition compared with no fertilizer addition, possibly because of accelerated biomass decomposition with N application. Over a 50-yr period, additional biomass and organic C produced by a high N fertilization rate increased the final infiltration rate in the Walla Walla silt loam by a factor of 2.4 (Zuzel et al., 1990). Saturated hydraulic conductivity (K_{sat}) in the Ap horizon

and in the tillage pan was maintained at a high level only when crop residue returns increased and soil pH was maintained above 5.6 (Pikul and Allmaras, 1986). Long-term use of N fertilizer also reduced soil pH (Rasmussen and Rohde, 1989), as a linear function of N applied, in both the MP and SW systems. Acidifying effects were concentrated in the upper 7 and 22 cm of the SW and MP system, respectively.

The Walla Walla silt loam is one of many Mollisols in the Pacific Northwest that contains a high concentration of potentially mobile Si, ranging from 40 to 100 mg SiO$_2$ kg^{-1} soil in the form of H$_4$SiO$_4$ (Douglas et al., 1984). Douglas et al. (1984) showed that the concentration of H$_4$SiO$_4$ in these soils increased as pH decreased, when base cations were leached out of the soil profile. Measurements of Si$_{ws}$, soil pH, amorphous Si, and total acidity in the same Walla Walla silt loam (Baham and Al-Ismaily, 1996) indicated that Si had leached from the upper Ap layer, illuviated into the lower Ap, and deposited in the boundary between the Ap and B horizons. Higher mechanical (penetrometer) resistance, especially in dry soils, has been reported by several investigators and was attributed to movement and deposition of Si at the 20- to 30-cm depth to form a weakly cemented siliceous plow pan (Douglas et al., 1984; Baham and Al-Ismaily, 1996; Wilkins et al., 2002).

Brown and Mahler (1987, 1988) hypothesized that acidification from long-term use of NH$_4^+$–based N fertilizers solubilized Si, which then illuviated and was retained as amorphous Si in the plow pan of Mollisols in Idaho. Water extracts of soil in well-developed plow pans had more Si than in poorly developed plow pans, while Si sorption occurred above and below the plow pans. Brown and Mahler (1988) concluded that Si concentrations in the plow pan were apparently controlled by amorphous Si deposit. These studies did not investigate the possible influence of SOC on soluble Si. Bloom and Nater (1991) showed that complex-forming ligands, such as carboxylic and phenolic acids, may cause dissolution of amorphous siliceous minerals to Si$_{ws}$, and that these weathering reactions are a forward dissolution.

Little or no research has examined the combined influence of tillage and N fertilization on SOC distribution, acidification profiles, and Si movement in a soil profile because of the complexity of interactions between soil constituents, climate, and soil management. Through the use of long-term field experiments, the relation of soluble Si to both SOC and acidification were examined in the context of soil management and C sequestration

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Abbreviations: ρ_b, bulk density; C_{ws}, water soluble carbon; COM, coarse organic matter; D, soil depth; FOM, fine organic matter; K_{sat}, saturated hydraulic conductivity; MP, moldboard plow tillage; Si$_{ws}$, water soluble Si; SOC, soil organic carbon; SON, soil organic nitrogen; SW, sweep tillage.

in this soil. Objectives of this study were to: (i) determine the effect of tillage and N fertilizer on SOC accretion in a Walla Walla silt loam, and (ii) then examine the influence of FOM and pH on Si movement and distribution in the soil profile.

MATERIALS AND METHODS

Site Description and Field Experiment

A long-term tillage and N fertility field experiment was initiated in 1940 (Rasmussen and Rohde, 1988, 1989), at the Pendleton Agriculture Research Center in northeastern Oregon (45° 43′ N, 118° 38′ W with 454-m elevation). The climate is semiarid with an annual mean temperature of 10.2°C and precipitation of 420 mm, 70% of which occurs mainly as winter rain during the period of 1 November to 30 April (Zuzel et al., 1993). The sampled experimental plots were located on a Walla Walla silt loam with slopes <2%. The tillage treatments are the main plots in a randomized block with N rates as subplots (Table 1). There were three replications in the original experiment but only two were sampled for this study. Main plots are 35 by 40 m, while subplots (N rates) were 5.8 by 40 m. There were three primary tillage treatments in the original experiment but only two extremes (MP and SW) were sampled. Secondary tillage after moldboard plowing in the MP system is one pass with a spring tooth cultivator and three or four rod weeding passes before wheat seeding, while secondary tillage after sweep tillage in the SW system is one skew treader pass and as many as four rod weeding passes as necessary between April and October. Of the five original N rates only two extremes (45 and 180 kg N ha^{-1}) were sampled. Nitrogen was broadcast as $(NH_4)_2SO_4$ from 1940 to 1961 and as NH_4NO_3 from 1962 to 1982. All N was surface applied shortly before the last secondary tillage in September. Wheat seeding was usually in September and October. Primary tillage for the summer fallow was performed in April 1982, a year before soil samples were taken. Details of the experiment including total N applied, soil acidity developed, and organic N and C content of the soil profile in 1984 were reported by Rasmussen and Rohde (1988, 1989). The cropping system is alternating summer fallow and winter wheat. Crop residues returned have been measured since 1978, and relative crop residues available after the 1981 harvest are representative of measurements since 1978.

Soil Sampling

Soil samples were taken on 19 April 1983 midway between wheat rows after the winter wheat had renewed growth in the spring. Cores were selected randomly within the inner two-thirds of the plot area (to avoid plot-to-plot contamination), using the soil sampling procedure described by Pikul and Allmaras (1986) and Allmaras et al. (1988b). A tube sampler was used to remove a soil core (l = 30 cm and i.d. = 18 mm) from the 0- to 30-cm depth. Each soil core was pushed out of the tube onto a half-round sampler tray that had a metric scale attached to the upper edge. A second soil core was removed from the 30- to 60-cm depth and sectioned into 2-cm increments, but the 50- to 60-cm depth increment was not sectioned. The 2-cm soil increments were cut with a spatula, separated, and placed into bags for storage. The sampler barrel minimized soil contamination once the soil core passed the cutting tip. There were 16 randomly selected cores for the 0- to 60-cm depth, each 18-mm in diam., per each of two replications of the four selected treatments. These 16 cores were composited to provide a soil mass in each 2-cm increment

Table 1. Description of the four treatments sampled from the long-term tillage and N experiment.

Primary tillage† (depth)	N rate	Estimated long-term N applied‡	Residue at harvest (1981)	Surface residue at seeding
		kg ha^{-1}		
Moldboard	45	570	8 820	220
(22 cm)	180	1780	10 870	−§
Sweep	45	570	7 860	2100
(15 cm)	180	1780	9 920	−

† Primary tillage to initiate summer fallow in April 1982. Secondary tillage involving spring tooth cultivator, skew treader, or rod weeder during summer fallow penetrated no deeper than 10 cm.
‡ Estimated N applied from 1940 to 1983 (Rasmussen and Rohde, 1989).
§ Not measured.

sufficient to separate out the incorporated crop residue and provide sufficient soil for later soil analyses, except organic N. Core count and quantitative soil transfer were both needed for accurate ρ_b determination. Soil cores were gently mixed with a spatula and air-dried. The oven-dry (105°C) soil mass (estimated from a subsample) and sample volume (number of cores, 2-cm increments and 18-mm diam.) were used to calculate ρ_b. All constituent properties were expressed on a volumetric basis using these ρ_b.

Coarse Organic Matter and Fine Organic Matter Separation

Air-dried soil samples were gently sieved over a 0.5-mm sieve (35 mesh), to avoid breaking up fresh and partially decomposed crop residue and to separate out this coarse crop residue (Allmaras et al., 1988b). The coarse crop residue fraction (plant residue with adhered soil particles) retained on the sieve (>0.5 mm) was further analyzed to determine the uncontaminated coarse crop residue. The residue fraction (>0.5 mm), containing some contaminant mineral soil, was air dried and weighed, a small subsample of the <0.5-mm separate was used to estimate oven-dried weight. A methodology (conservation of C procedure) developed by Allmaras et al. (1988b) was used to estimate the weights of contaminating mineral soil and coarse residue particles free of soil. This fraction is designated as COM. The term FOM is used for soil material with organic matter that passed through the sieve (<0.5 mm) to distinguish this fraction from the COM fraction containing predominantly particulate material. The air-dried crop residue fraction (>0.5 mm) and a subsample of the FOM fraction (<0.5 mm) were each ball milled with SPEX/Mixer/Miller (Model 8000, SPEX Industries, Inc. Scotch Plains, NJ)[1]. Total C was determined for both fractions with a Leco carbon analyzer (Leco Corp., St. Joseph, MI). Selected analysis showed that none of these soil samples contained inorganic C. Gentle sieving and the C conservation procedure minimized particulate organic matter contamination of FOM. This separation of COM and FOM was made only in the top 30 cm, which exceeds the deepest depth of residue incorporation by the MP.

Particulate material is frequently separated by flotation (Gregorich and Ellert, 1993; Carter and Gregorich, 1996) to expose sequestered C. However, such a procedure would have required additional soil sampling, compromised the integrity of the long-term plots, and lost the precision associated with multiple analyses on the same sample.

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[1] Mention of trade names or commercial products in this manuscript is solely for the purpose of providing specific information, and does not imply recommendation or endorsement by the USDA.

Soil pH, Water Soluble Carbon, and Silica Measurements

Part of the air-dried and ball milled soil fraction (<0.5 mm) used for the determination of SOC in FOM was used for additional soil measurements. Soil pH was measured in duplicate for each soil sample using a 1:2 (w/w) soil to 0.01 M $CaCl_2$ ratio.

To analyze for C_{ws} and Si_{ws}, 5 g of air-dried soil was added to 25 mL of deionized water in a flask, shaken for 30 min, allowed to settle overnight, centrifuged (12 000 $\times$ g) for 10 min, and filtered (Whatman No. 40). Filtrate aliquots were used for soluble C (C_{ws}) and Si (Si_{ws}) determinations. Water-soluble C was analyzed as oxidizable C (Technicon Industrial Systems, 1976; Douglas et al., 1984) present in the aqueous filtrate. An aliquot of the filtrate in the auto analyzer stream was exposed to a high velocity stream of CO_2–free air in a turbulent liquid film to remove any inorganic C contaminant. The carbonate free stream was then mixed with an acid and persulfate stream, before exposure to ultraviolet radiation to convert organic C to CO_2. The CO_2 was collected into a turbulent liquid film stream and reacted with a weakly buffered phenolphthalein indicator. The original C concentration was colorimetrically determined. One aliquot per soil sample was analyzed for C_{ws}.

Silicic acid in the aqueous filtrate was determined using a modified heteropoly blue method (Rand et al., 1975; Technicon Industrial Systems, 1976; Douglas et al., 1984). Ammonium molybdate at pH 1.2 reacts with Si and any phosphate contaminant to produce heteropoly acids. First a 0.03 M HCl solution was introduced into the auto analyzer sample stream to dilute the aliquot, and oxalic acid was added to eliminate phosphate interference before ascorbic acid addition. Silicomolybdate in acidic solution formed a molybdenum blue color and was assayed colorimetrically.

Soil Organic Nitrogen Estimation

The data sets for SON in the top 26 cm used here are from an experiment reported earlier (Rasmussen and Rohde, 1988). They reported total N as organic N, because inorganic N was <1% of total N. Soil organic N (g N kg^{-1}) was converted to mg cm^{-3} using ρ_b profiles measured as described above. Any change in SON between 1983 and 1984/1986 was assumed to be negligible.

Statistical Procedures

Nested ANOVA and GLM procedures (SAS Institute, 1988) were used for statistical analysis. The nested ANOVA was used to compute a root mean square error from which the standard error of the mean was computed from duplicate composites (replications) corresponding to treatment $\times$ soil property $\times$ depth. Significant differences among treatment means ($P < 0.05$) were tested using t tests. Multiple linear regression and ANOVA in GLM were used to estimate parameters and statistical significance.

RESULTS AND DISCUSSION

Management Effects on Bulk Density, pH, and Coarse Organic Matter

Profiles of ρ_b were characteristic of primary tillage tools (Fig. 1a). Moldboard plowing with secondary tillage produced a ρ_b profile, which had a maximum at the 20-cm depth, minimum at 10- to 18-cm depth, and a 2- to 10-cm layer that was uniformly repacked by secondary tillage. Sweep tillage produced a 5- to 20-cm layer with nearly uniform ρ_b, which did not distinguish the sweep shear plane from soil repacked by secondary tillage.
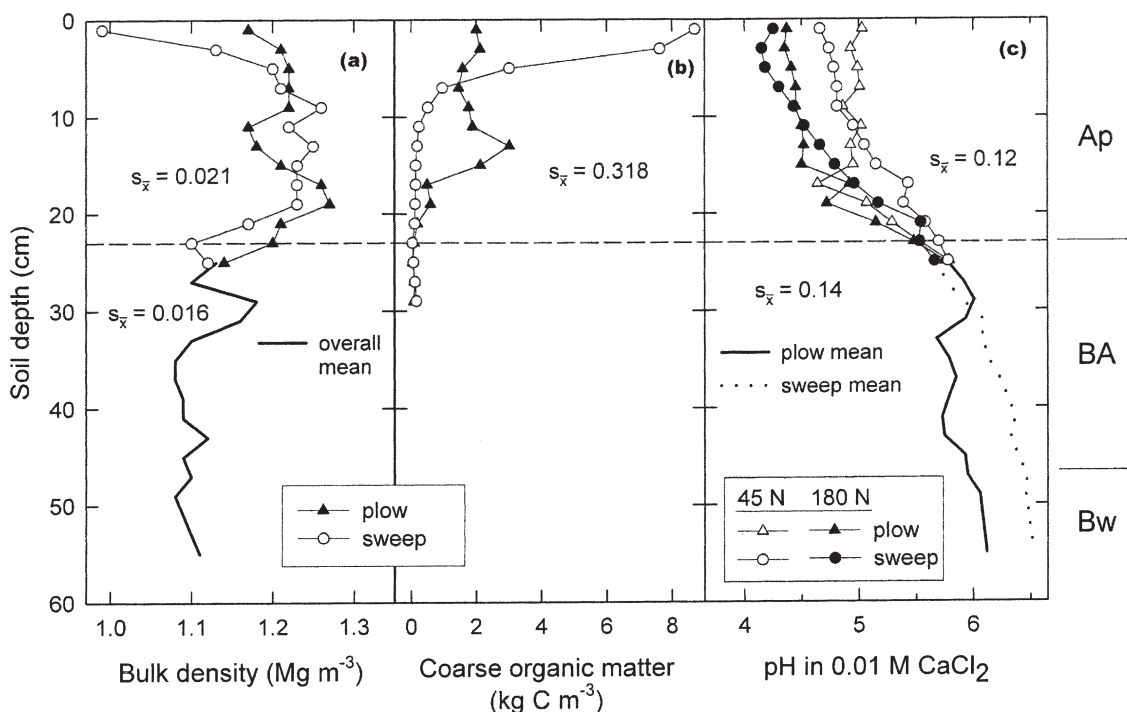

Fig. 1. Profiles of (a) soil bulk density (ρ_b), (b) coarse organic matter (COM), and (c) soil pH with depth, as related to primary tillage and N fertilizer rate (the S_x has 12 and 13 d.f. in Ap and B horizons, respectively).

The overall ρ_b values below the 25-cm depth were not sensitive to tillage systems.

Coarse organic matter profiles were also characteristic of primary tillage (Fig. 1b). The MP system produced a nearly uniform COM concentration from 0- to 11-cm; however, the concentration increased at the 11- to 17-cm depth. The increased COM concentration at the 11- to 17-cm depth corresponded well with decreased ρ_b at about the same depth. Moldboard plowing inverts residue, such that the largest concentration of fresh residue occurs below 15 cm (Allmaras et al., 1988a, 1996), depending on tillage depth. Residue retention for the SW system was highest near the surface and declined exponentially with soil depth (Fig. 1b), somewhat similar to a chisel tillage system (Allmaras et al., 1988a, 1996). An integrated value of COM (Table 2) is about 11% of FOM and is about 75% of the C in the shoot residue produced at the last harvest.

Profiles of pH in the Ap horizon (Fig. 1c) were sensitive to primary tillage and applied N rate. Application of 180 kg N ha^{-1} decreased pH more than the 45 kg N ha^{-1} rate in the Ap horizon for both primary tillage systems. The nearly unchanged pH profile of the MP system, down to the 17-cm depth, was most likely due to N leaching that ultimately reached the buried residue zone, because the N application is made at a shallow depth nearly 7 mo after the last moldboard plowing. Moreover, the crop residue is buried when moldboard plowed. Years of N fertilization and moldboard plowing could have contributed to uniform pH in the plow layer for the MP system. The pH profiles in the 0- to 10-cm depth for the SW system were more acidic than in the MP system for both fertilizer rates. This can be explained by intimate residue and fertilizer contact close to the soil surface at the time of fall seeding. This was illustrated by higher COM concentration at the 0- to 7-cm depth for the SW system (Fig. 1b). The increased residues in the SW system could contribute to organic

acid production that would decrease soil pH in addition to acidification from the N fertilization. However, the acidification potential from the NH_4NO_3 is greater than from organic acids.

The MP system significantly ($P < 0.05$) decreased soil pH in the B horizon by an average of 0.54 units compared with the SW system even down to 55 cm (Fig. 1c). Rasmussen and Rohde (1989) attribute the greater MP effect on pH values, as compared with SW, to a greater denitrification rate in the SW than the MP system. The overall decrease in mean pH due to higher fertilizer rate (data not shown in Fig. 1c) was only 0.02 and 0.30 units for the SW and MP systems, respectively. However, the small pH responses to N rate for the two tillage systems in the B horizon were reversed from their juxtaposition in the Ap horizon.

Management Effects on Fine Organic Matter, Water-Soluble Carbon, and Water-Soluble Silica

Tillage had a consistently larger effect on FOM than did N rate (Fig. 2a), even though the 180 kg N ha^{-1} rate increased wheat residue production approximately 25% compared with the 45 kg N ha^{-1} rate (Table 1). The 180 kg N ha^{-1} treatment had consistently more FOM in the Ap horizon than did the 45 kg N ha^{-1} treatment, however the difference was not statistically significant (Fig. 2a). The profile distribution of FOM in the top 12 cm was similar to the profile distribution of COM (Fig. 1b) with respect to the primary tillage treatment.

Soluble C distribution profiles in the Ap horizon corresponded with FOM profiles (Fig. 2b). Nitrogen rate treatments influenced C_{ws} relatively more than FOM, especially in the SW system, but primary tillage influenced C_{ws} and FOM similarly. The N rate and the primary tillage system (SW > MP) each increased total C_{ws} significantly ($P < 0.10$) in the Ap horizon (Table 2). There were no significant treatment effects on total C_{ws} in the B horizon, therefore an overall mean was shown. Total C_{ws} was about 3% of FOM C in both the Ap and B horizon.

Primary tillage influenced the Si_{ws} content with depth in the Ap horizon. The Si_{ws} substantially increased with depth in all treatments, however the high N rate significantly ($P < 0.05$) decreased mean Si_{ws} for both tillage systems as much as 16% compared with the low N rate (Fig. 2c, Table 2). A maximum concentration just above the B horizon implies solubilization, movement and ultimately deposition within the lower Ap horizon. Tillage treatment effect on Si_{ws} in the 20- to 26-cm layer was unusually small. No treatment effects on Si_{ws} were noted in the B horizon, where the overall mean concentration was relatively unchanged as a function of depth, and was significantly ($P < 0.05$) greater than in the Ap horizon (Table 2). No tillage differential was observed (Table 2), even though the depth distribution of Si_{ws} was markedly sensitive (Fig. 2c). At the 45 kg N ha^{-1} rate, Si_{ws} concentrations in the B horizon were 34 and 39% greater than in the Ap horizon for the MP and SW systems, respectively.

Table 2. Tillage and N rate effects on total amount of coarse organic matter (COM), fine organic matter (FOM), soil organic N (SON), water-soluble carbon (C_{ws}), and water-soluble silica (Si_{ws}) in Ap horizon (0–26 cm) and sampled B horizon (26–60 cm) in the tillage by N experiment.†

Tillage	N rate	Soil horizon	COM	FOM	SON	C_{ws}	Si_{ws}
	kg ha^{-1}		kg C m^{-2}		kg N m^{-2}	g C m^{-2}	g Si m^{-2}
Moldboard	45	Ap	0.31	3.41	0.27	78.2	24.2
		B	–‡	2.28	–§	63.4	32.4
	180	Ap	0.39	3.50	0.30	85.7	20.1
		B	–	2.25	–	73.7	33.4
Sweep	45	Ap	0.50	3.79	0.31	85.0	23.7
		B	–	2.57	–	65.6	33.0
	180	Ap	0.38	3.93	0.33	98.3	20.2
		B	–	2.64	–	66.8	31.7
SE¶			0.08	0.14	0.01	6.7	0.9

† COM > 0.5 mm expressed as C; FOM < 0.5 mm expressed as C; Si_{ws} water-soluble silica as Si.
‡ COM carbon in B horizon not shown; values ranged from 0.003 to 0.008 kg C m^{-2}.
§ Not measured.
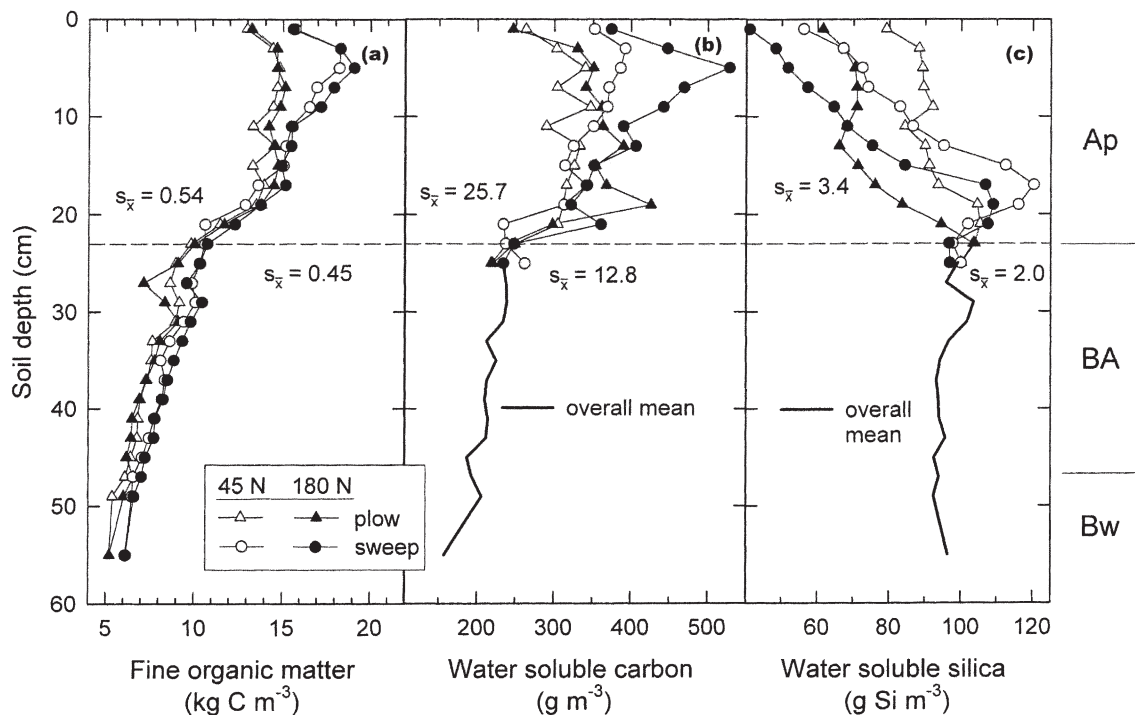¶ The SE in the Ap horizon had 12 df, while that in the B horizon had 13 df.

Fig. 2. Profiles of (a) fine organic matter (FOM), (b) water-soluble carbon (C_{ws}), and (c) water-soluble silica (Si_{ws}), as related to primary tillage and N fertilizer rate (the S_x has 12 and 13 d.f. in Ap and B horizons, respectively).

Tillage and N fertilizer rate had a significant ($P < 0.05$) effect on SON content (Table 2). The SON contents in the MP system (0.27 and 0.30 kg N m^{-2} for low and high N rates, respectively) were lower than in the SW system (0.31 and 0.33 kg N m^{-2}).

Soil Organic Carbon Storage in the Fine Organic Matter Fraction

Primary tillage systems had a stronger effect on SOC storage than N fertilization in both Ap (0–26 cm) and B horizons (26–60 cm). The SW system had a significantly ($P < 0.05$) and consistently greater FOM storage than the MP system in the Ap (especially above 15 cm) (Fig. 2a and Table 2). Mean FOM was 3.46 and 3.86 kg C m^{-2} in the Ap horizon, and 2.26 and 2.60 kg C m^{-2} in the B horizon, for the MP and SW systems, respectively (Table 2). These FOM differences were statistically ($P < 0.05$) significant for both comparisons. Greater FOM in the B horizon for the SW compared with the MP system suggests more below ground biomass under the SW system. We suggest that this could be due to more moisture and a deeper rooting system under the SW than the MP tillage system, or because of an accelerated decomposition rate under the MP system. Soil water-storage is greater in the SW than MP treatments when the soil is moldboard plowed in the fall (Douglas et al., 1992). This effect is also likely when spring moldboard plowed.

Mean FOM for the 45 and 180 kg N ha^{-1} rates were 3.60 and 3.72 kg C m^{-2} in the Ap horizon, respectively; the difference was statistically ($P < 0.05$) significant. However, the SOC storage of 2.43 and 2.45 kg C m^{-2} for the two N rates were not different in the B horizon. Greater SOC storage in the B horizon for tillage system compared with N rate cannot be explained by shoot growth because the mean crop residue at harvest in 1981 was 25% greater due to the high N rate (Table 1). Accelerated residue decomposition with high N application could have resulted in lower SOC storage.

The SW system significantly ($P < 0.05$) increased the mean SOC storage in the FOM fraction, for both fertilizer rates, in the Ap and B horizons by 11.9 and 15.0%, respectively, compared with the MP system (Table 2). Mean SOC storage in the FOM fraction for the 180 kg N ha^{-1} treatment was 6.6 and 5.8 kg C m^{-2} for the SW and MP system, respectively, in the 0- to 60-cm soil depth (Table 2). Total FOM (6.6 kg C m^{-2}) in the SW system was 14% higher (5.8 kg C m^{-2}) than in the MP system. These are lower than the estimated SOC storage of 6.9 kg C m^{-2} in the upper 50 cm of soil in Haploxerolls reported by Kern et al. (1997).

Interaction of Soil Organic Carbon Components

Three components of SOC are COM, FOM, and C_{ws}. Both COM and FOM distribution profiles were sensitive to primary tillage and N rate (Fig. 1b and Fig. 2a). A multiple linear regression (F-ratio, $P < 0.05$) model depicted the general relationship of these two SOC components in the Ap horizon as follows:

$$FOM = \alpha + \beta_1 (COM) + \beta_2 (\rho_b) + \beta_3 (D) \ (R^2 = 0.63)$$
[1]

where units of both COM and FOM are in kg C m^{-3}; ρ_b is in Mg m^{-3}; D is soil depth in cm; $\alpha = 0.26$; $\beta_1 = 0.28$; $\beta_2 = 13.33$; and $\beta_3 = -0.199$.

There was a positive relation between FOM and COM ($\beta_1 = 0.28$), because long-term use of the same tillage system controls COM position. This in turn controls FOM distribution in the soil profile subject to the influence of wheat rooting biomass. The ρ_b decreased as COM increased (Fig. 1a). The COM burial did not reach the base of the Ap horizon, where ρ_b was greater because of a tillage pan. Greater COM and lower ρ_b were observed between the maximum tillage depths, as secondary tillage with a cultivator may redistribute residue toward the surface (Allmaras et al., 1996). Bulk density has decreased as much as 12% in small soil volumes that contained COM (Allmaras et al., 1996).

The third component of SOC, C_{ws}, was measured from the same soil samples used to measure FOM. The C_{ws} increased in the Ap horizon of both tillage treatments as the N fertilizer rate increased. The mean ratio of C_{ws} to FOM within the Ap horizon was 0.023. The C_{ws} values were likely a maximum because soil samples were obtained during April, when soil moisture and temperature were suitable for residue decomposition (Douglas et al., 1980). A larger fraction of FOM was in the C_{ws} form in the B relative to the Ap horizon (Table 2). Higher C_{ws} in the B than Ap horizon could be due to leaching. Douglas et al. (1984) observed that C_{ws} leached from the 0- to 15-cm layer and accumulated below 15 cm in a controlled leaching study using soil from the same field plots.

Treatment-Induced Changes in Fine Organic Matter and pH Related to Water-Soluble Silica Responses

Soil management that changes SOC storage and soil pH can impact Si_{ws}. Profiles of Si_{ws} were sensitive to tillage and N rate in the Ap horizon (Fig. 2c and Table 2). A multiple linear regression was used to examine the influence of soil constituents on Si_{ws}. The dependent variable, Si_{ws}, was regressed to the independent variables, pH, FOM, ρ_b, and D:

$$Si_{ws} = \alpha' + \beta_1' (pH) + \beta_2' (FOM) + \beta_3' (\rho_b) + \beta_4' (D) \ (R^2 = 0.83)$$
[2]

where Si_{ws} units are in g Si m^{-3}; FOM units are in kg C m^{-3}; ρ_b units are in Mg m^{-3}; D units are in cm; $\alpha' = -139.51$; $\beta_1' = 20.52$; $\beta_2' = -1.46$; $\beta_3' = 115.70$; and $\beta_4' = 0.43$. This equation accounted for 83% of Si_{ws} variability. All regression coefficients were statistically significant ($P < 0.01$) except that for D was significant ($P < 0.20$). The positive coefficient for pH is consistent with acidification of amorphous Si, due to N fertilization, as necessary for Si_{ws} leaching from the upper portion of

Table 3. Simple correlations between soil pH, fine organic matter (FOM), soil bulk density (ρ_b), soil depth (D) and water-soluble silica (Si_{ws}) in the Ap horizon.

	pH	FOM	ρ_b	D	Si_{ws}
pH	1.00				
FOM	−0.76	1.00			
ρ_b	−0.02	0.22	1.00		
D	0.75	−0.73	0.07	1.00	
Si_{ws}	0.79	−0.62	0.39	0.73	1.00

the Ap horizon. The negative coefficient for FOM indicated more crop residue and sequestered SOC reduced Si_{ws} content, which is consistent with Douglas et al. (1984). They reported less leaching of Si_{ws} as FOM increased. The regression coefficients for both ρ_b and D are indicative of their influence on Si_{ws} in the lower parts of the Ap horizon.

Simple correlations (Table 3) between Si_{ws} and pH were large and positive. The correlation between Si_{ws} and FOM was large and negative, and that between Si_{ws} and ρ_b was positive and small. The large negative correlation between pH and FOM (Table 3) is consistent with effects of N fertilization. The large correlations of D with pH and D with FOM are consistent with Fig. 1c and Fig. 2a, respectively.

Higher N rates increased FOM and decreased pH as well as Si_{ws} in the upper parts of the Ap horizon (Fig. 1c and 2c). Douglas et al. (1984) observed Si leaching from the 0- to 15-cm layer and accumulation in lower layers; the respective loss and accumulation were larger with the higher N application. The 180 kg N ha^{-1} treatment had the lowest pH and highest total SOC. Acid forming N fertilization (Barak et al., 1997) was shown to increase mineral weathering.

The general shape of the Si_{ws} profile (Fig. 2c) is similar to those of Brown and Mahler (1987, 1988) in Idaho, as well as Baham and Al-Ismaily (1996) on the Walla Walla silt loam. Lower Si_{ws} concentrations were found in the Ap horizon than in the B horizon, with the highest concentration at the boundary between horizons at about the 20-cm depth. Brown and Mahler (1987, 1988) reported a high concentration of polymerized amorphous Si in the plow pan zone. Baham and Al-Ismaily (1996) found a large amorphous Si concentration in the Ap horizon of Walla Walla silt loam that was insensitive to several long-term N fertilizations, but their water soluble Si concentration was much lower and sensitive to the N fertilizations.

Our measurements in producer's fields within 50 km from the research plots (not shown) showed soil profiles of Si_{ws}, FOM, and pH similar to those in this study. These sites, mostly MP system, were more intensively managed with respect to N fertilization, various crop sequences, and supplemental irrigation.

A constant but limited supply of Si_{ws} in this soil can be expected because the less soluble siliceous minerals (biogenic opal, volcanic glass, and other amorphous minerals) can undergo dissolution in the presence of organic

ligands. Higher Si_{ws} concentrations found in the B horizon than in the Ap horizon, with the highest concentration at the boundary between horizons, is most likely the result of dissolution of amorphous Si to Si_{ws} and subsequent leaching. Bloom and Nater (1991) showed that complex-forming ligands, such as carboxylic and phenolic acids, might cause dissolution of amorphous siliceous minerals to Si_{ws}. However, the decrease in pH associated with N fertilization did not increase Si_{ws} in the presence of high FOM concentrations produced by the increased biomass (Fig. 1c and Fig. 2c).

CONCLUSIONS

Tillage and N fertilizer effects on SOC and Si_{ws} were examined in a wheat-fallow cropping system on a Walla Walla silt loam. Tillage treatments had a greater impact on SOC storage in both the Ap and B horizons than N fertilization. The SW system retained 14% more SOC than the MP system in the 60-cm profile; whereas, the 180 kg N ha^{-1} rate increased SOC storage only 3% over the 45 kg N ha^{-1} rate. Long-term use of the same tillage system determines COM position, which in turn controls FOM distribution. The FOM always increased as COM increased. The SW system increased FOM storage in the Ap and B horizon by 12 and 15%, respectively, compared with the MP system. The N rate treatments influenced C_{ws} relatively more than FOM, but primary tillage influenced C_{ws} and FOM similarly. Both the N rates and the primary tillage system increased the total amount of C_{ws} in the Ap horizon. However, there were no significant treatment effects on total C_{ws} in the B horizon. Total C_{ws} was about 3% of FOM C in the Ap and B horizons. Concentration of C_{ws} increased in the Ap horizon for both tillage treatments as the N fertilizer rate increased. Mean Si_{ws} concentration in the Ap horizon for both tillage systems was significantly decreased by 16% with the 180 kg N ha^{-1} N rate.

Profiles of COM, FOM, and ρ_b were all characteristic of tillage systems. Profiles of pH, $C_{ws,}$ and Si_{ws} were related to tillage and N fertilizer. The pH profiles with SW system at the 0- to 12-cm depth were more acidic than with MP system for both fertilizer rates. The MP treatment decreased soil pH by an average of 0.54 units compared with the SW treatment in the B horizon. Lower Si_{ws} concentrations were found in the Ap horizon than in the B horizon, with the highest concentration at the boundary between horizons. A decrease in pH associated with N fertilization did not increase Si_{ws} in the presence of high FOM concentrations. Interaction of tillage and N with Si_{ws} suggests that SOC provides a mechanism to reduce Si solubility. Therefore, crop residue management has an important impact on Si solubility and movement. This may be especially important at the interface of the Ap and B horizons, where siliceous pan formation increases mechanical resistance to root penetration, impairs drainage and reduces plant growth and production.

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